Low Profile Design for Intrepid to Assess, Measure and Harvest RF Energy

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Abstract

A low profile design which could be used in order to analyze RF energy in near home premises is presented in this paper. The system design is intended to practice in the real world in an easy, economical and DIY way. The idea was to detect the possible source of RF energy that could be harvested even for a short span. A monitoring unit which is microcontroller with two patch antennas, each with a two stage schottky diode voltage multiplier acting as its sensors look for a potential RF energy (Bi-directional only) as soon unit powered up, then unit compare and record the strength of nearby RF energy which is provided as feedback to a servo motor. A rectenna, which is mounted on the top of the servo motor, is made responsible to measure and harvest RF energy. The DC power from the harvesting rectenna is used to power digital thermometer with an LCD module. A low profile prototype is implemented, tested locally and found with acceptable performance.

Keywords: *Energy harvesting, Measurement, Rectennas, Schottky diode, Sensor System.*

1. Introduction

Emerging self powered systems challenge and dictate the direction of research in energy harvesting (EH). State of the art in energy harvesting is being applied in various fields using different single energy sources or a combination of two or more sources. This kind of environmental friendly energy sources include energy harvesting from rectennas, passive human power, wind energy and solar power. Power we can extract from those techniques is limited by regulations and free-space path loss. As a general idea, small dimensions are a basic feature of portable devices, so the rectenna should be the same way. [17] Smaller the size results in the received power to be lower. This made wireless power transfer suitable for the low-power applications, e.g., a low-power wireless sensor.

The way technology advance every year allow the decrease of certain characteristics in digital systems, like size and power consumption, that will lead to the gain of new ways of computing and use of electronics, as an example we have wearable devices and wireless sensor networks. Currently, these devices are more powered by batteries, however, they present many disadvantages such as: the need to either replace them or recharge them periodically and their big size and weight compared to high technology electronics. A solution proposed to this problem was stated before: to extract (harvest) energy from the environment to either recharge a battery, or even to directly power the electronic device. [3][20]

Targeted RF energy is in the ambient or areas close to transmission towers provides an opportunity to harvest that energy. Some of the most prominent sources are FM radio systems ((88-108 MHz, transmitted power few tens of KW), TV Transmission (180-220 MHz, transmitted power few tens of KW), Cell Tower Transmission (10 to 20 W per carrier), Wi-Fi (2.45GHz, 5.8GHz), AM Transmission (540-1600 KHz, transmitted power few hundred KW) and mobile phones (transmitted power 1W to 2W), etc. [15] Cell towers can be used as a continuous source of renewable energy as they transmit 24 hours.

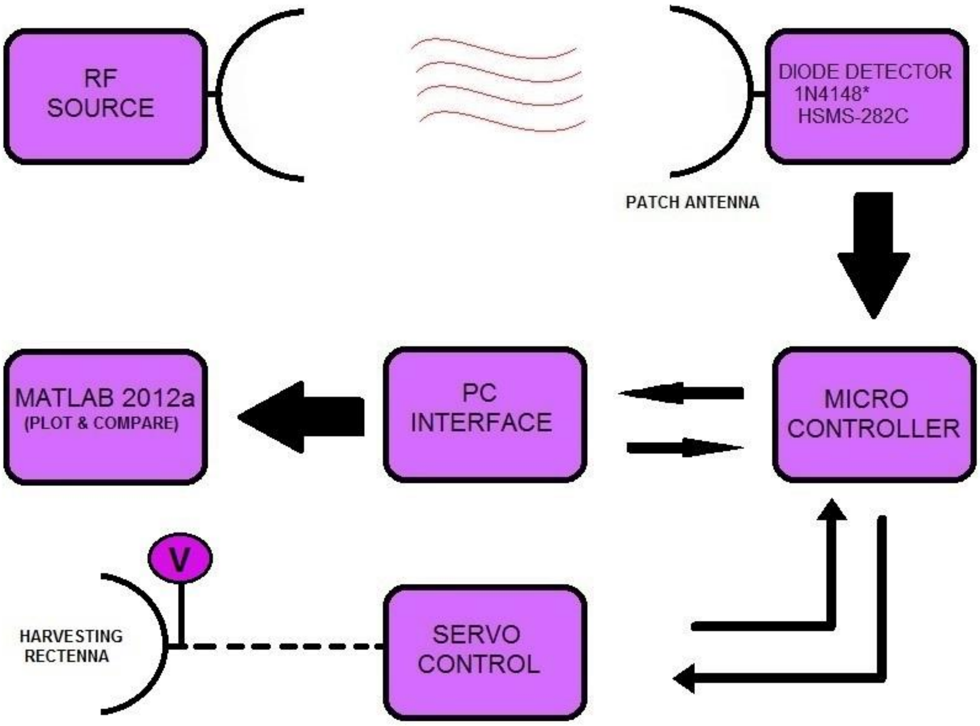


Fig. 1: a) Detailed Block Diagram for proposed system. (V-voltmeter)

Fig 1 presents the basic functionality of the system:

1. First, an antenna is in charge to capture the RF signals from the possible source of interest (CDMA-GSM Band).
2. Then a zero bias diode detector circuit (voltage multiplier) will convert RF-DC (carrier power) which will be input to the monitoring unit.
3. The Arduino Uno (open source hardware as monitoring unit) is used to read real time analog data from the voltage multiplier and will send it to PC via an interface.
4. Matlab R2012a software is used to read digital data values available at pc port and to plot it in terms of voltage, compare the signal and put command to control servo motor of the measuring Rectenna.
5. Servo motor will get a command from Matlab R2012a via microcontroller unit and also sent back feedback voltage for current position.
6. Finally the measuring rectenna will be on target RF source to measure electric field strength and display it in terms of voltage on the voltmeter.

Several operating frequencies for the rectenna have been investigated in the literature. Traditionally the GSM900 band has been utilized due to the presence of 2G networks; additionally the 1800 MHz band has also been considered which implies a smaller antenna aperture area than that of 900MHz. Both frequency bands present similar advantages because they have comparably low atmospheric loss, cheap components availability, and high conversion efficiency.[4][8] Hence the frequency bands corresponding to mobile telephone systems such as 800 MHz, 900 MHz and 1800MHz present good alternatives for electromagnetic energy harvesting systems, although they require a larger antenna size.

2. Design

In order to be able to utilize wireless power efficiently rectenna is needed. This paper presents a rectenna system with numerical and test observations. This provides a good insight of low profile system for the wireless power assessment and utilization. The incident RF power is converted into dc power by the voltage multiplier. The matching network, composed of inductive and capacitive elements, ensures the maximum power delivery from antenna to voltage multiplier. The energy storage (output capacitor) ensures smooth power delivery to the load and as a reserve for durations when external energy is unavailable. Such a design needs to be carefully crafted: increasing the number of multiplier stages gives higher voltage at the load, and yet reduces the current through the final load branch. [17]

This work has three major goals:

1. Measurement of stray radiation in term of Electric field intensity (V/ m).
2. RF energy harvesting/recycling.
3. Powering of low-power applications.

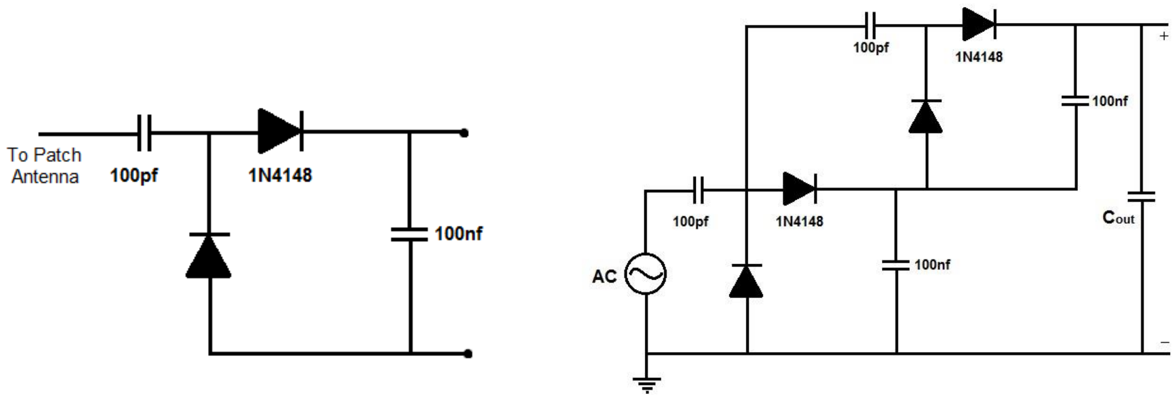
2.1. Voltage multiplier and diode selection

The forward voltage drop (V_f), reverse-recovery time (T_{rr}), and junction capacitance (C_j) of Schottky diodes are closer to ideal than the average “rectifying” diode. This makes them well suited for high-frequency applications. Unfortunately, though, Schottky diodes typically have lower forward current (If) and reverse voltage (V_{rrm} and V_{dc}) ratings than rectifying diodes and are thus unsuitable for applications involving substantial amounts of power, Though they are used in low voltage switching regulator power supplies. [23]

The Schottky diodes used are characterized by a low parasitic capacitance C_{jo} (0.14 pF) and a low serial resistor R_s (20 Ω). At microwave frequencies, rectifiers are highly nonlinear and difficult to design based upon purely analytic equations. Commercially available harmonic-balance simulators are useful at low power levels.

When looking for a rectifying diode in the context of RF recycling, a diode with high conversion efficiency, even for very small incident power levels is required. One of the crucial requirements for the energy harvesting circuit is to be able to operate with weak input RF power. For a typical 50-ohm antenna, the -20 dBm received RF signal power means amplitude of 32 mW. As the peak voltage of the ac signal obtained at the antenna is generally much smaller than the diode threshold [12], diodes with lowest possible turn on voltage are preferable. Moreover, since the energy harvesting circuit is operating in high frequencies, diodes with a very fast switching time need to be used. [17] Schottky diodes use a metal–semiconductor junction instead of a semiconductor–semiconductor junction. This allows the junction to operate much faster, and gives a forward voltage drop of as low as 0.15 V.

Earlier the choice was using Fairchild’s 1N4148 small signal diodes and 1N5819 Schottky rectifiers. But the study presented in [22] gave a broad view of there operation under various condition determine that the previous diodes having higher forward voltage requirement as compared to Hsms 282c and the capacitance of the diode’s is higher as well .The final rectifier circuit is designed using Hsms 282c Schottky Diode. Avago’s Hsms-282x family of zero bias Schottky detector diodes are already designed and optimized by manufacturer for use in small signal (Pin >-20 dBm). They are ideal for RFID and RF Tag applications where primary (DC bias) power is not available. [13][14]

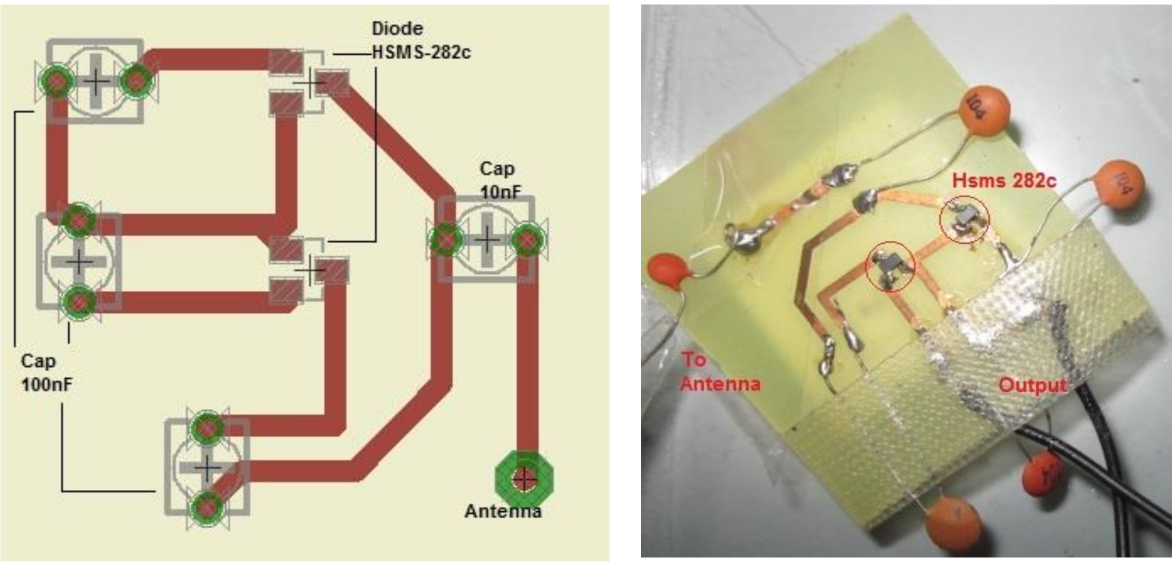


a) **b)**

Fig. 2: a) Single stage diode detector. b) Two stage diode detector with output capacitor.

The fig. 2 above presents the two types of diode detectors on of which (b) is full wave rectifier (known also as a two stage diode voltage doubler). Such a circuit offers several advantages. First the voltage outputs of two diodes are added in series, increasing the overall value of voltage sensitivity for the network (compared to a single diode detector). Second, the RF impedances of the two diodes are added in parallel, making the job of reactive matching a bit easier. [14]

The number of rectifier stages has a major influence on the output voltage of the energy harvesting circuit. [17] Each stage here is a modified voltage multiplier, arranged in series. The output voltage is directly proportional to the number of stages used in the energy harvesting circuit. However, practical constraints force a limit on the number of permissible stages, and in turn, the output voltage. Here, the voltage gain decreases as number of stages increases due to parasitic effect of the constituent capacitors of each stage, and finally it becomes negligible.[13]

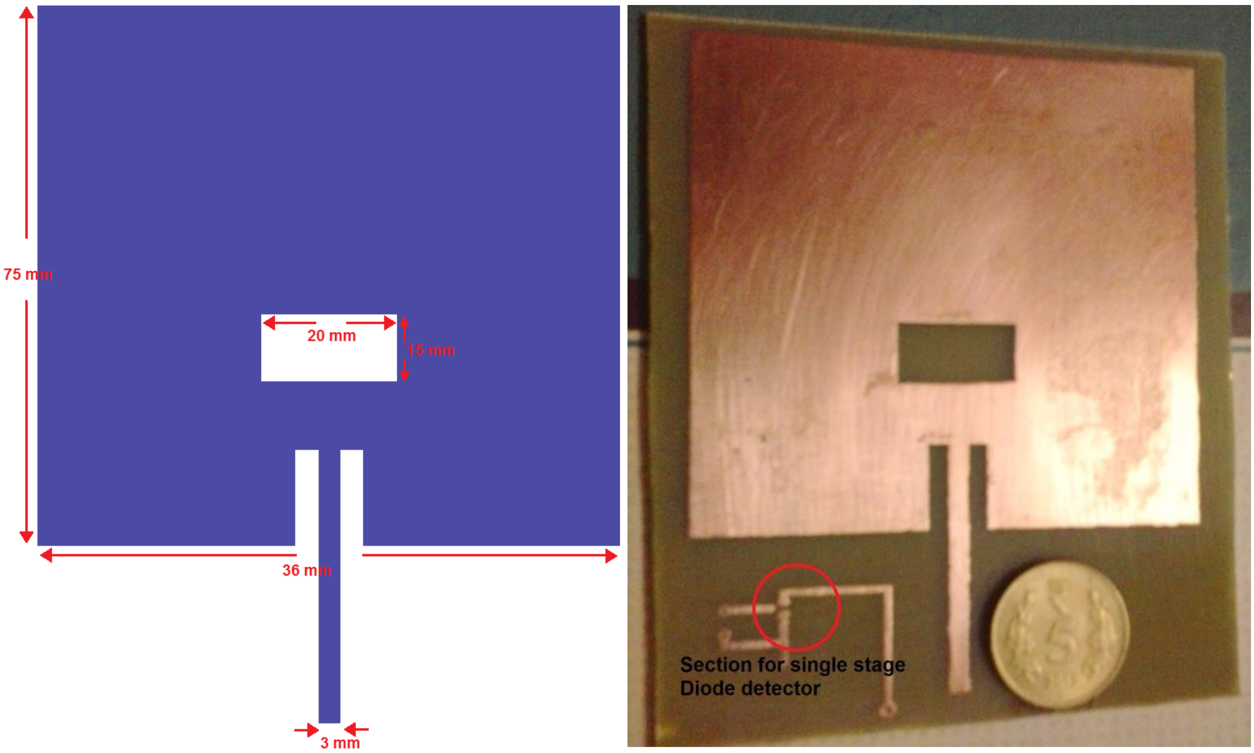


a) b)

Fig. 3: a) PCB layout for voltage multiplier b) Fabricated two stage voltage multiplier with HSMS-282c.

2.2. Rectenna

The word rectenna is composed of rectifying circuit and antenna. The rectenna and its word were invented by W. C. Brown in 1960's. [2] The rectenna can receive and rectify a microwave power to DC, is passive element with a rectifying diode, operated without any power source. The antenna of rectenna can be any type such as dipole, Yagi-Uda antenna, microstrip antenna, monopole, coplanar patch, spiral antenna, or even parabolic antenna. The rectenna can also take any type of rectifying circuit such as single shunt full-wave rectifier, full-wave bridge rectifier, or other hybrid rectifiers. The circuit, especially diode, mainly determines the RF-DC conversion efficiency; rectennas with FET or HEMT appear in recent years. (The rectenna using the active devices is not passive element). [2]



a) b)

Fig. 4: Modified Inset-feed Patch Antenna with Dimensions a) CAD design with dimension b) Fabricated patch on FR4

A circular polarized microstrip patch antenna in fig 4 a) and b) above (86 mm x 75 mm) has been associated with the rectifier to obtain the complete rectenna design. The antenna simulation was carried out using the electromagnetic simulator Ansoft HFSS v.11 [9]. The closest to desired resonant frequency has been achieved and matched in a single simulation. It showed a good input matching level at 886 MHz.

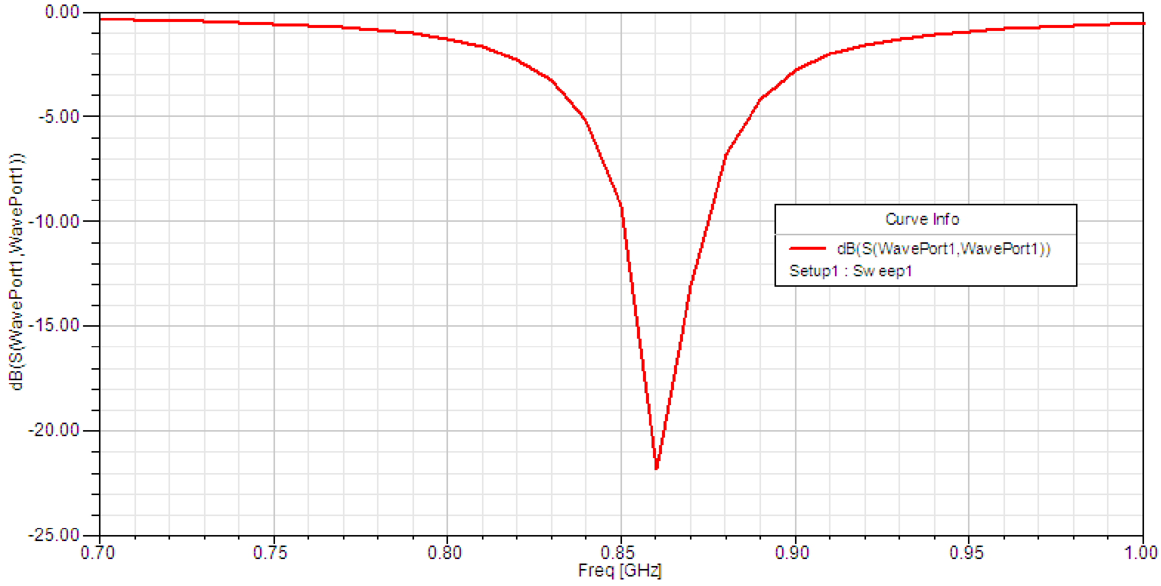
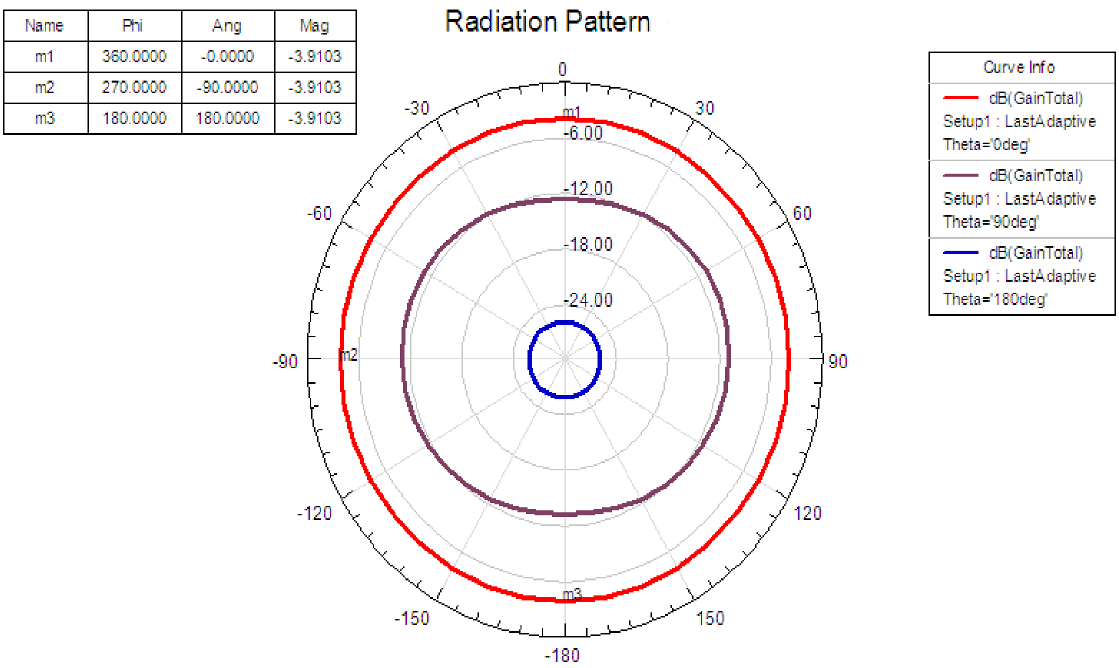


Figure 5: Return Loss (S_{11}) of Microstrip antenna.



Name	Phi	Ang	Mag
m1	360.0000	-0.0000	-3.9103
m2	270.0000	-90.0000	-3.9103
m3	180.0000	180.0000	-3.9103

Figure 6: Radiation Gain plot of Microstrip antenna.

After simulating the structure figure 5 above showing return loss (S_{11}) of the patch antenna structure .The plot gives return loss of ~21.9 dB at 886 MHz. Figure 6 is the radiation gain plot of the microstrip antenna at 886 MHz from three major angles of 0, 90 and 180 degree which is showing the maximum gain as -3.91dB.Here point t ponder is although the bandwidth of antenna is ~25 MHz still it could be used to beyond that band. The problem that will occur using this antenna beyond its resonant band is mismatched impedance and it will not produce maximum/efficient output.

The purpose of the inset cut in the patch is to match the impedance of the feed line to the patch without the need for any additional matching element. This is achieved by properly controlling the inset position. Hence this is an easy feeding scheme, since it provides ease of fabrication and simplicity in modeling as well as impedance matching. However as the thickness of the dielectric substrate being used, increases, surface waves and spurious feed radiation also increases. The feed radiation also leads to undesired cross polarized radiation. [17][11]

The three essential parameters for the design of a rectangular Microstrip Patch Antenna are:

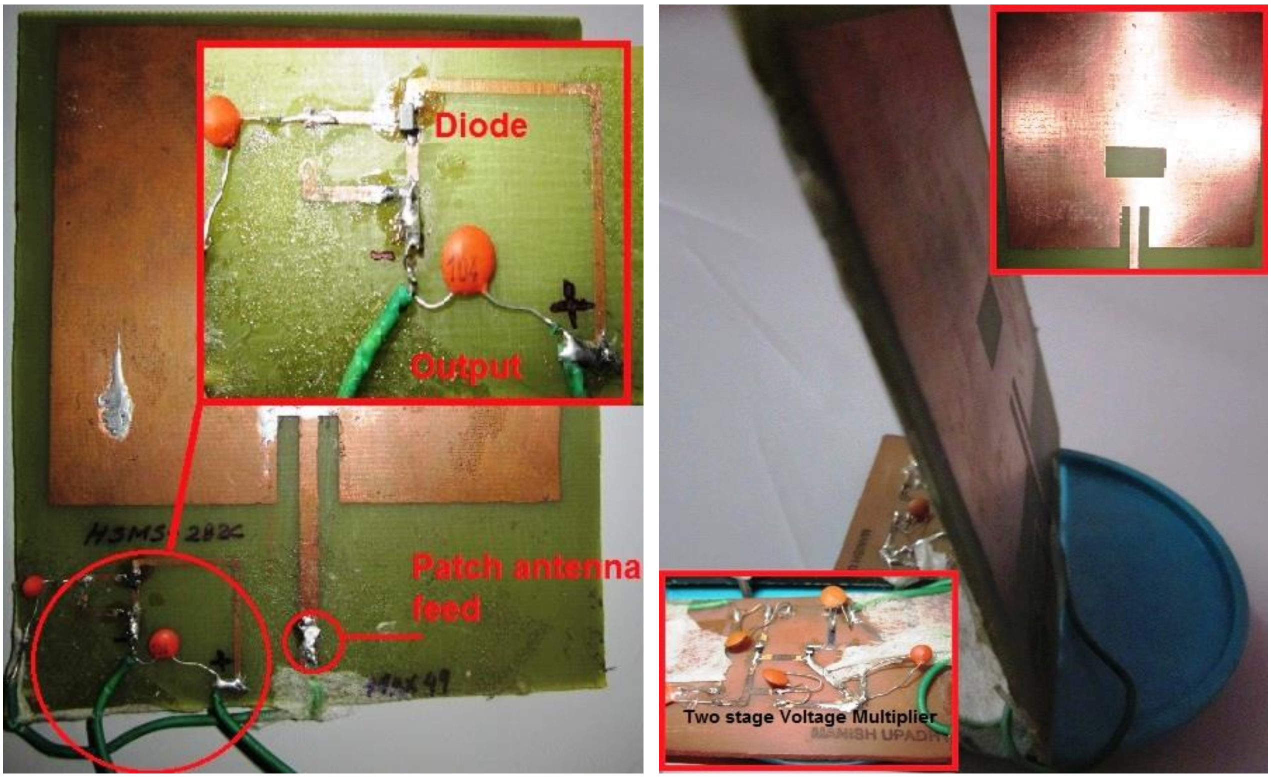
- Frequency of operation (fo) : 886 MHz
- Dielectric constant of the substrate (εr) : 4.4
- Height of dielectric substrate (h) : 1.6 mm.

The parameters obtained using the formulas for inset feed [11] are:

- Total width of the antenna (W) : 86 mm
- Total length of the antenna (L) : 75 mm
- Effective Dielectric Constant (εreff) : 3.9262

At higher frequencies such as 800 or 1900MHz the low values of inductors are difficult to construct especially at board level circuit design. But using the inductor along with capacitor at integrated circuit level design greatly improves the performance. Resonant frequency is also influenced by diode capacitance as it is related with reverse diode voltage and input voltage. [6][23]

In order to test single and double stage voltage multiplier output both are fabricated on a Copper clad sheet (FR4).the single stage detector is embedded with the patch antenna as in fig.7 a) while the two stage diode detector is attached with patch antenna on it back side can be seen in inset of fig.7 b).



a) b)

Figure 7: Fabricated patch antenna with a) single stage diode (HSMS-282c) detector b) two stage diode (BAT-16) detector (voltage multiplier).

Some effects were previously observed by many researchers is that the circuit yields the optimal efficiency at a particular load value, that is, the circuit's efficiency decreases dramatically if the load value is too low or too high. Since the energy harvesting circuit consists of diodes, which are nonlinear devices, the circuit itself exhibits nonlinearity. This implies that the impedance of the energy harvesting circuit varies with the amount of power received from the antenna. Since the maximum power transfer occurs when the circuit is matched with the antenna, the impedance matching is usually performed at the particular input power. [17]

The RF signals can be captured using Multiband antenna such as quad band are easily available in market and usually work at 900MHz/1800MHz/1900MHz/2.4GHz. These are of usually whip type, but small size such as printed, patch, spiral antennas are also testable. A tuning capacitor (C_{tune}) is used to capture the maximum power at required frequency range. Using only Clamp capacitor in antenna matching circuit we can tune the antenna at its resonant frequency. The tuning Capacitor (C_{tune}) can be verified by using the following formula to resonate with antenna inductance ($L_{antenna}$), where f is the frequency of operation.

$$2\pi f = \frac{1}{\sqrt{L_{antenna} \times C_{tune}}} \qquad 1.$$

f = Reasonant Frequency
C_{tune} = Tuning Capacitor
$L_{antenna}$ = Antenna Inductance

3. Test and Observation discussion

As per the block diagram representation the system required a (CDMA-GSM) RF source with known power level that is served by BTS tower near the lab. It is well known that in India the mobile tower have major band of operation in 877MHz-915MHz. For measurement it needs to determine the power at specified distance that is measured by Spectrum Analyzer and my four stages diode detector using 1N4148 is used earlier. Antenna for transmitting is assumed omni-directional whip antenna. While the antenna used in case of measurement of standard emission by RF source is measured using helical wire (unmatched) antenna on spectrum analyzer port and a copper patch for IN4148 diode detector.

Since the test receiver/detector used was a very low profile diode detector using 1N4148 (Semiconductor-semiconductor junction) which is having forward voltage drop ~620mV at 1mA and 1V at 15mA which is not an efficient value for the required application. For the final tests 1N4148 design is neglected and Schottkey Diodes (zero bias) like HSMS-282C AND BAT-16 that is designed for having very low forward voltage drop (approx. 340mV & 580mV respectively) and high switching speed is used.

3.1. Testing at external site

Setup shown in fig. 8 is a copper patch attached with two stage diode voltage multiplier to test electric field strength in vicinity of mobile phone tower. In order to make comparison of the electric field strength (V/m) near mobile phone tower antenna one needed to calculate ideal value of power that should be received and then the practical value measurement.

a) **b)**

Fig 8: Rectenna
a) using two stage schottkey diode detector b) Testing at external site (cell tower)

For calculation of ideal radiation figures/component certain parameters are assumed (on the basis of previous presented reports and data from Indian ministry of telecommunication site). These considerations could have deviation from standard one which may be the possible cause of difference reflected in practical measurement. Below present equation 2 to 7 are standard equations that are used with FRISS Model to calculate ideal values and to convert measured value. [17]

Parameters:

Frequency of interest (f) = 900 MHz (Between CDMA and GSM band)

Largest radiator dimension (D) = approx. 1 meter

Wavelength in meters (λ) = 0.33 meters

Typical Base station power (single carrier per operator) (Pt) = 10 watts/2 watt (amended Indian limit for radiation).

Typical Transmitter Antenna gain (Gt) = 17 dB

Receiver Antenna gain assumed to be (Gr) = -3.9 dB = -1.75 dBi (calculated with simulation model)

$$\mathrm{P_r} = Ae.\mathrm{E}.\mathrm{H} \tag{2.}$$

$$Ae = g\frac{\lambda^2}{4\pi} \tag{3.}$$

$$E = Z_o.\mathrm{H} \tag{4.}$$

$$Z_o = 120\pi = 377\Omega \tag{5.}$$

$$S = \frac{E^2}{Z_o} \tag{6.}$$

$\mathrm{P_r}$ = Power received (W)
Ae = Antenna aperture (m)
E = Electric field strength (V/m)
H = Magnetic field strength (A/m)
λ = Wavelength (m)
g = Antenna gain
Z_O = Impedance (Ohm)
S = Power density (W/m2)

The **Fraunhofer** distance (d):

$$d = \frac{2.\mathrm{D}^2}{\lambda} = 6m \tag{7.}$$

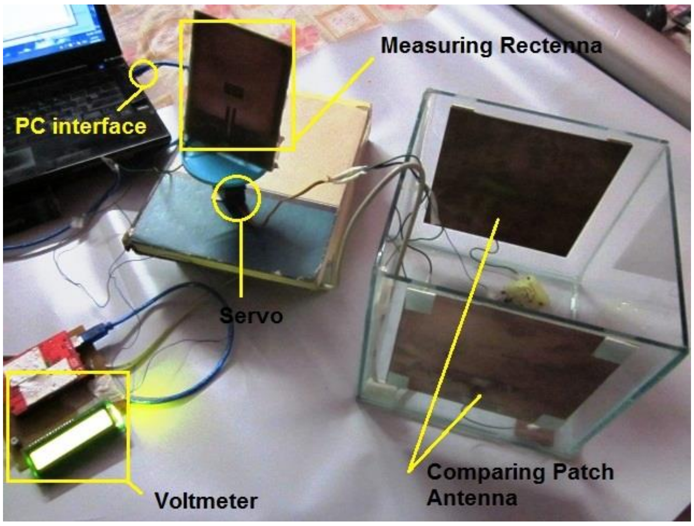
During measurement practice its is to be ensure that measurement is taken by maintaining minimum distance from cell tower because the Friss model of calculation that is to be used to estimate power received valid over far field only. The observations are presented in the table 1.Some quick conclusion that could be made is the test site reading are closer to ideal value one with the 2W/carrier standard.

Distance from Source	Power & Electric Field density (Ideal)			Power & Electric Field density strength Received (Test site)		
15 meter	177.3 mW/m^2	8.16 V/m	18.94 dBm	15 mW/m^2	2.44 V/m	-10.31 dBm
	35 mW/m^2	3.63 V/m	11.90 dBm			
30 meter	44 mW/m^2	4.07 V/m	12.89 dBm	6.7 mW/m^2	1.62 V/m	-13.97 dBm
	8.8 mW/m^2	1.82 V/m	5.90 dBm			
50 meter	15.9 mW/m^2	2.35 V/m	8.22 dBm	3.2 mW/m^2	1.1 V/m	-17.23 dBm
	3.1 mW/m^2	1.08 V/m	1.37 dBm			

Table 1: Test results comparison with ideal calculated values while mobile tower as RF source and two stage diode detector as receiver. Ideal transmitted power values correspond to RED = 10W/carrier & BLUE = 2W/carrier

3.2. Testing with the combined system

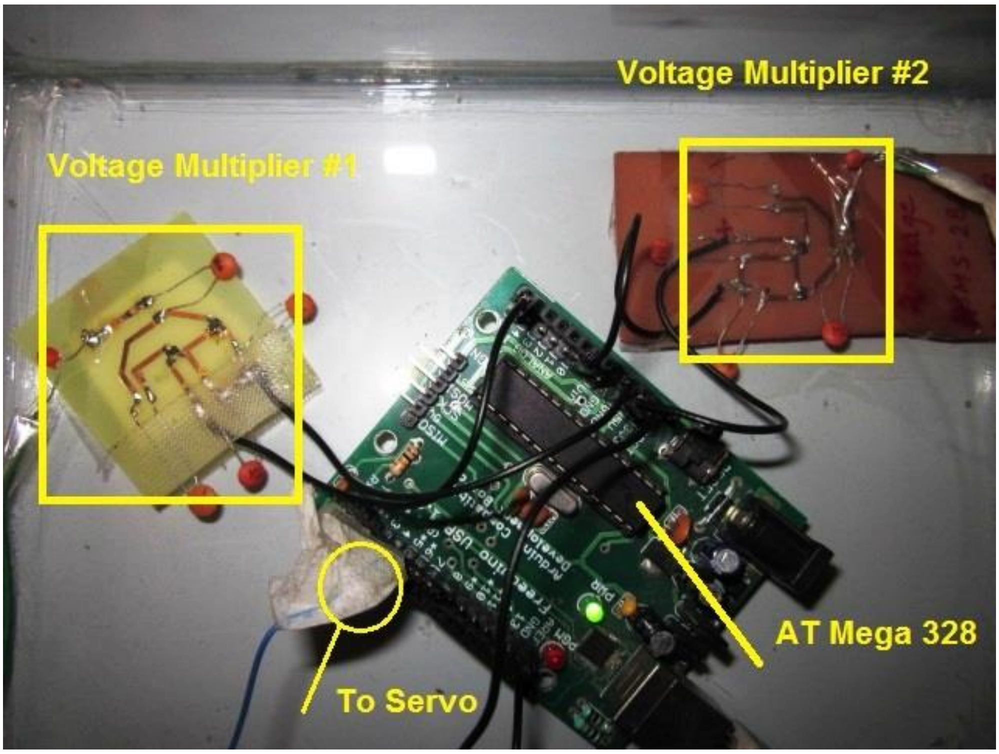
The combined system is presented in fig 9 a) which includes a glass container used to house two patch antennas connected with separate voltage multiplier which can be seen in fig 9 b) are connected to arduino uno (open source hardware platform with atmega-328) to its analog input pins. The measuring rectenna is mounted over a servo motor, which is controlled by the monitoring unit (microcontroller atmega-328).The voltmeter which is designed to measure electric field strength (V/m) is connected to the output of measuring antenna. The data to the analog pin of arduino uno is converted to equivalent digital bits and fed to laptop. The Matlab 2012a program on the laptop will collect data from arduino uno.



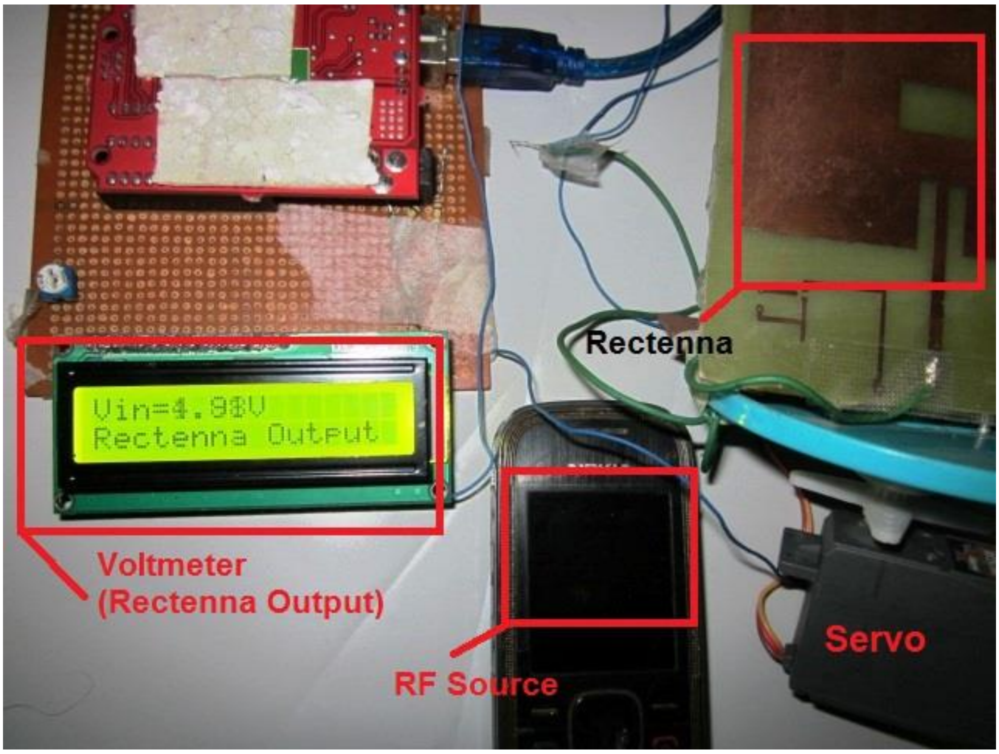
a)

When an RF source (CDMA-GSM band) like an operating cell phone with call initiated is brought near the measuring rectenna will result into an output voltage on voltmeter (field strength) as shown in fig 9. A program file written in the Matlab 2012a software which is for comparing output from the monitoring unit if executed, will start the arduino uno (monitoring unit); patch antenna on both the side of glass structure will start working to provide the strength of nearby field which will be input to the analog pins of arduino uno. Further the monitoring data will be fed to Matlab 2012a program executing on its way. The program will start plotting a real time graph of two voltages (for both the side of glass structure); on the basis of the relative strength of both antennas the program will command servo via arduino uno to move/target measuring rectenna toward the major RF source. In Fig. 9 c) the cell phone with a call initiated brought near the measuring rectenna, which result into an output of ~4.9V as pulsating DC is displayed on voltmeter LCD. Once the program is manually started in Matlab 2012a its activate both the patch antenna attached with monitoring unit as a result we can see the fig. 10 .The patch antennas are marked as right and left are assigned with color marker in Matlab 2012a graph plot. In Fig. 10 we can see that initially voltage plot is high due to the cell phone setting up communication with nearest tower. Another point we can notice is that the cell phone and the rectenna facing to the left side of the glass structure result into the left patch receiving most of the RF radiation.

Once we move RF source (cell phone) away from left side result into decreasing strength of RF radiation recorded by the blue line (left patch antenna) on the plot Eventually moving toward the right of the glass structure rise the RF strength recorded by right Patch antenna which will result into high red line strength on the plot. When the red line (right patch) record higher strength than a blue line (left patch),



b)



c)

Figure 9: Combined system testing a) complete prototype operation, b) circuit inside glass structure, c) measuring rectenna output on voltmeter.

The program will command servo to move measuring rectenna position (facing) from left to Right side .In this way, system will keep on comparing the strength and will automatically move measuring antenna toward more RF strength.

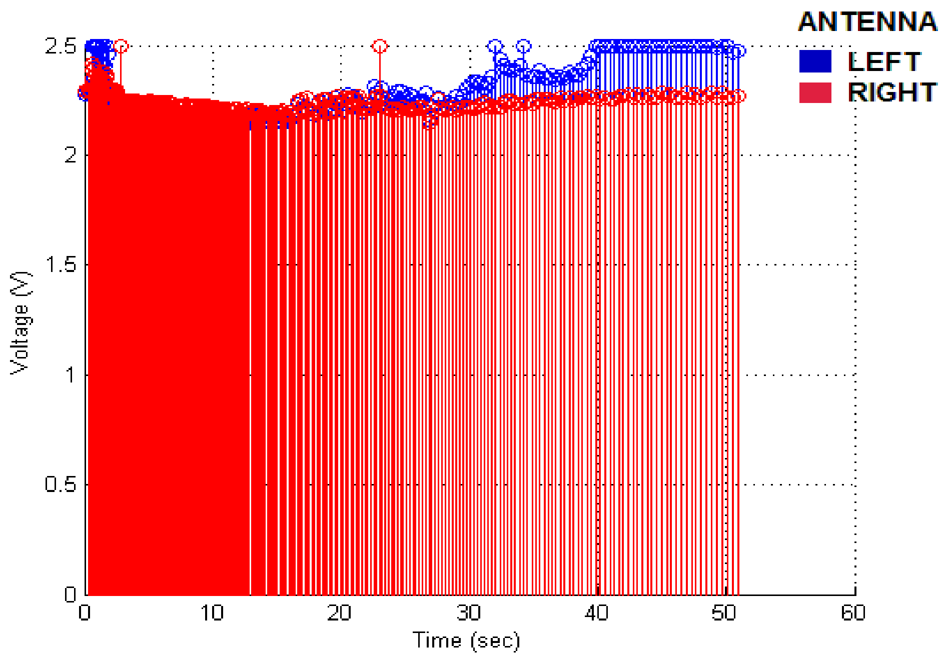
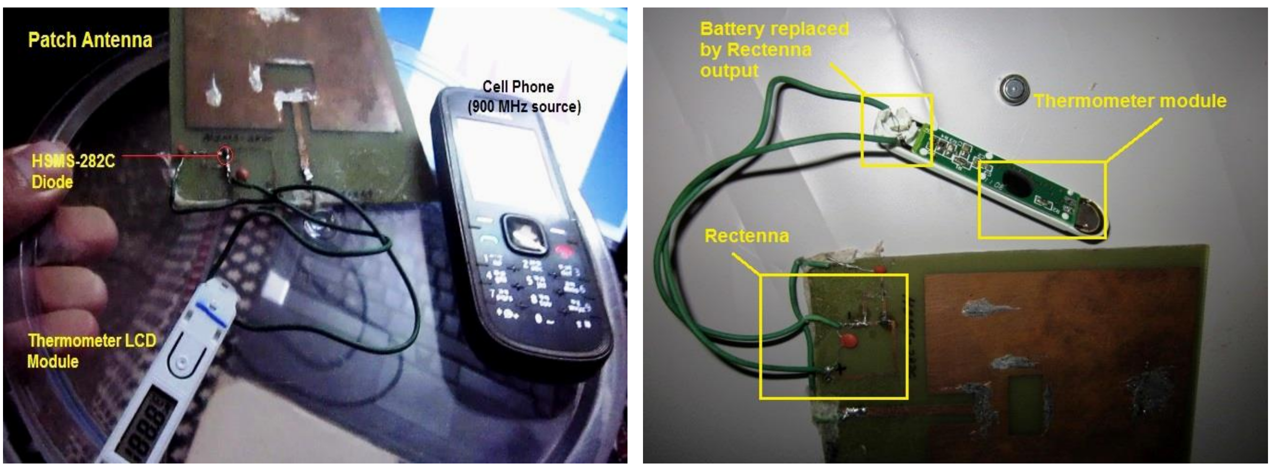


Figure 10: Plot for patch antenna on left (blue) and right (red) side of monitoring unit.

3.3. Powering LCD thermometer module

In fig 11 above presented a practice to power up an LCD thermometer module using the rectenna and a cell phone. As in fig 11 b) we can see that the battery from the thermometer module is replaced by rectenna output. Here in this case the wire connected to the battery section of the thermometer module is nothing but the output of single stage zero biased diode detector using (HSMS-282c), which will convert RF current to DC. When we brought a cell phone with an initiated call result in rectenna to provide dc voltage to the thermometer module as could be seen in fig. 11 a) the LCD on thermometer module start operating. Once the call terminated the rectenna stopped providing dc output result in the power to Thermometer module get down in very short span. Although the thermometer is able to operate for the very short span during an operating cell phone call still it is verified that power is enough to operate module but a consistent source of RF energy or a capacitor with low leakage and possibly with high discharge time.



a) b)

Figure 11: LCD thermometer module a) powered by rectenna using cell phone as RF source, b) Battery is replaced by rectenna output.

4. Conclusion

A low profile RF (CDMA-GSM) energy measuring and harvesting system has been analyzed, designed and tested. The novel idea is to track/target the RF energy in real time to measure and harvest it. Voltage multiplier configurations, has been verified and optimized by means of test series conducted in lab and external site. Although no input low pass filter is used for rejection of harmonics at the input power of the rectifier still results gives good agreement to theoretical calculations.

A low profile inset-feed modified patch antenna is developed and used. A silicon based schottky diode single stage and 2 stage rectifiers are designed and fabricated on copper clad sheet (FR4). Comparison of ideal and RF energy measured with rectenna at test site with cell towers is presented.

Low series resistance Schottky diode in single stage detector is used to implement rectenna which could successfully power up the LCD thermometer. Although the power is not consistent for long use but system could be improved using super capacitor as output load of rectenna to operate low power devices.

Finally such system could be developed to be prove effective in charging of mobile handset (primary device) by placing to be charged mobile handset (secondary device) very close to fully charged mobile handset and draining primary device energy for charging the secondary device. Higher performance can be achieved by implemented the circuit in low sub micron manufacturing processes. Output voltage level can be increased using multiple stages of the multiplier circuit.

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